A METHOD OF PLASMA ETCH ENDPOINT DETECTION USING A V-I PROBE DIAGNOSTICS

By Inventors:

Armen Avoyan
Francois Chandrasekar Dassapa
Brian McMillin

BACKGROUND OF THE INVENTION

[0001] The present invention generally relates to methods and control systems for improving semiconductor processing results and, in particular, to methods of detecting an endpoint for dielectric etching.

[0002] Plasma processing systems have been around for some time. Over the years, plasma processing systems utilizing inductively coupled plasma sources, electron cyclotron resonance (ECR) sources, capacitive sources, and the like, have been introduced and employed to various degrees to process semiconductor substrates and glass panels.

[0003] During processing, multiple deposition and/or etching steps are typically encountered. During deposition, materials are deposited onto a substrate surface (such as the surface of a glass panel or a wafer). For example, deposited and/or grown layers including various forms of silicon, silicon dioxide, silicon nitride, metals and the like may be formed on the surface of the substrate. Conversely, etching may be performed to selectively remove materials from predefined areas on the substrate surface. For example, etched features such as vias, contacts, and/or trenches may be formed in the layers of the substrate. Some etch processes may utilize chemistries and/or parameters that simultaneously etch and deposit films on the plasma-facing surfaces.

[0004] The plasma can be generated and/or sustained using a variety of plasma generation methods, including inductively-coupled, ECR, microwave, and capacitively-coupled plasma methods. An example plasma processing system of the capacitively-coupled type is

shown in FIG. 1 and indicated by the general reference character 150. Many of the components of plasma processing system 150 are conventional and may be found in, for example, the Exelan® family of plasma etchers (e.g., 2300 Exelan® Flex), which is available from Lam Research Corporation of Fremont, CA.

[0005] In FIG. 1, plasma processing system 150 includes a chamber 100, which provides an enclosure for processing as well as defining an exhaust passageway by way of a vacuum pump (e.g., "Pump") for exhausting etch byproducts. Chamber 100 is grounded in this exemplary plasma processing system. An upper electrode 104, which is also electrically grounded in the example of FIG. 1, functions as the etchant source gas (e.g., "Feedgas") distribution mechanism. Etchant source gas is introduced into the chamber via an inlet and is distributed in the plasma region 102 between upper electrode 104 and an electrostatic chuck (ESC) 108, which is disposed above a lower electrode 106. Wafer 109 for processing can be positioned on ESC 108.

[0006] Lower electrode 106 is energized by a radio frequency (RF) delivery system, which includes RF Matching Network 110 and RF power supply 118. V-I Probe 112 may be coupled to RF Matching Network 110 output to measure parameters furnished by RF power supply 118 for feedback control purposes. In the example of FIG. 1, RF power supply 118 supplies both about 2 MHz and about 27 MHz frequencies to lower electrode 106. When the RF supply furnishes RF power to lower electrode 106 and through ESC 108, a plasma is ignited and sustained in the plasma region 102 for etching Wafer 109.

[0007] The probe sensor (V-I Probe 112) is positioned downstream from the RF supply and generally as close to the ESC as possible. There may be maintenance concerns, however, that limit how close to the ESC the probe can be positioned. As one example, V-I Probe 112 may be about 8-9 inches from the ESC. V-I Probe 112 and digital signal processor (DSP) 114 may be part of an integrated commercial product. One such commercially available probe product is VI-PROBE-4100 Frequency Scanning Probe®, which is available from MKS ENI Products of MKS Instruments, Inc., Andover, MA. Another such commercial product is SmartPIM™, which is available from Straatum Processware, Ltd. (formerly Scientific Systems, Ltd.), of Dublin, Ireland. Each such commercial product can detect voltage, current, and phase parameter information for a variety of RF supply frequencies. Further, each can provide

harmonics for these parameters via Fast Fourier Transform (FFT) or other suitable methods in the DSP. Accordingly, signals 122 of plasma processing system 150 can include all associated harmonics of each parameter measured by V-I Probe 112. Etch Process Module Controller 116 can then use this information to control one or more plasma processing steps.

[0008] A common process control for etching applications in plasma systems is endpoint detection. Traditional methods for determining endpoints include: (1) laser interferometry and reflectivity; (2) optical emission spectroscopy; (3) direct observation; (4) mass spectroscopy; and (5) time-based prediction. By far, optical emission spectroscopy or optical means is the most widely used method in conventional plasma processing approaches. For many processing steps, such as applications where the exposed area is around 50% (e.g., metals), optical emissions may work fine. However, the sensitivity of this approach is limited by the etch rate and the total area being etched. In particular, optical endpoint detection is generally not robust for high aspect ratio dielectric etches, such as vias. Many such dielectric etches typically have a very low exposure area, such as perhaps only 1% of the total surface area of the oxide or dielectric film. Optical approaches become less and less reliable as technology scales for these applications.

[0009] More recently, usage of parameters from commercially available probe systems as described above have been used in attempts to detect endpoints. Such approaches have generally used a specific parameter, typically a fundamental waveform, for endpoint detection. However, such an approach may not be the most sensitive endpoint detection method for different types of etching and/or processing step. Hence, known approaches may not be well suited for a production environment. Common problems of known approaches include handling variations in production wafer-to-wafer environments and low sensitivity in low exposure area etching processing steps.

[0010] What is needed is a flexible endpoint detection method that can be adapted and optimized for different etching steps in a process and that is suitable for a production environment. In particular, a more reliable way of detecting endpoint in some applications, such as dielectric etch processing steps, is needed.

SUMMARY OF THE INVENTION

[0011] According to one embodiment of the invention, a plasma processing control system can include: a V-I probe for effectively monitoring a plasma processing chamber, where the probe can provide electrical parameters in response to a radio frequency (RF) supply (e.g., about 2 MHz, about 27 MHz, or about 60 MHz), a processor coupled to and/or included with a commercially available probe product that can provide harmonics for each of the electrical parameters, and a controller coupled to the processor that can select at least one of the electrical parameters and one of the associated harmonics for endpoint detection for a plasma processing application. The electrical parameters can include voltage, phase, and current and the plasma processing application can be dielectric etching. A system according to embodiments of the invention may be particularly suited for dielectric etching in a production environment.

[0012] According to another embodiment of the invention, a method for detecting an endpoint can include the general methods of performing a manufacturing endpoint detection calibration and performing production environment endpoint detection. The performing of a manufacturing endpoint detection calibration can include the steps of: (i) performing a plasma etching on a sample wafer; (ii) empirically determining a selected harmonics plot to detect an endpoint; and (iii) obtaining harmonics parameters that indicate the endpoint. The performing of a production environment endpoint detection can include the steps of: (i) performing the plasma etching on a production wafer; (ii) obtaining the selected harmonics plot; (iii) analyzing the selected harmonics plot to detect the endpoint; (iv) continuing the plasma etching if the endpoint is not detected; (v) discontinuing the plasma etching if the endpoint is detected; and (vi) performing any post-endpoint activities.

[0013] These and other features of the present invention will be described in more detail below in the detailed description of the invention and in conjunction with the following figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements and in which:

[0015] FIG. 1 is a cross-section view of a conventional plasma processing system with a V-I probe.

[0016] FIG. 2 is a flow diagram of a manufacturing lab endpoint detection calibration method in accordance with an embodiment of the invention.

[0017] FIG. 3 is a flow diagram of a production environment endpoint detection method in accordance with an embodiment of the invention.

[0018] FIG. 4 is a graph of voltage harmonics waveforms for endpoint detection in accordance with embodiments of the invention.

[0019] FIG. 5 is a graph of phase harmonics waveforms for endpoint detection in accordance with embodiments of the invention.

[0020] FIG. 6 is a graph of a current harmonic waveform for endpoint detection in accordance with embodiments of the invention.

[0021] FIG. 7 shows, in accordance with an embodiment of the present invention, an implementation involving multiple V-I probes.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0022] The present invention will now be described in detail with reference to a few preferred embodiments thereof as illustrated in the accompanying drawings. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art, that the present invention may be practiced without some or all of these specific details. In other instances, well known process steps and/or structures have not been described in detail in order to not unnecessarily obscure the present invention. The features and advantages of the present invention may be better understood with reference to the drawings and discussions that follow.

[0023] As discussed above, the V-I probe can be used to measure current, voltage, and phase parameters. In addition, harmonics for each can be determined through signal processing (e.g., DSP 114 of FIG. 1). These harmonics, including the fundamental or first harmonic, can be considered in an endpoint detection method according to embodiments of the invention. Further, these methods are adaptable to different frequency choices, as provided by, for example, RF power supply 118 of FIG. 1. Methods according to embodiments of the invention allow for the selection of a particular parameter and associated harmonic most suitable for endpoint detection at a given RF frequency. For example, in a particular embodiment, a second harmonic of a voltage parameter for an about 2 MHz RF signal can be used to reliably detect an endpoint. The methods of selecting this frequency, harmonic, and parameter for optimal endpoint detection for a particular application will be discussed in more detail below.

[0024] According to embodiments of the invention, a manufacturing endpoint detection calibration method and a production environment endpoint detection method are provided. Generally, the manufacturing endpoint detection calibration method can allow for the selection of the best harmonic and parameter for a given frequency for endpoint detection. In addition, the production environment endpoint detection method can allow for the process control of endpoint detection for a variety of process steps in a production environment.

[0025] In a manufacturing lab environment, a general method according to embodiments of the invention may be as follows. A test etching of a number of wafers (e.g., 2 to 100) may be performed. Each of the available harmonics (including the fundamental) may be reviewed to determine which harmonic for which parameter will give the best signature at the endpoint. Further, in order to allow for process variations in a production environment, an appropriate wafer should be chosen for the test etching. For example, a "nominal" process wafer may be chosen in order to best center the detection margin.

[0026] Referring now to FIG. 2, a flow diagram of a manufacturing lab endpoint detection calibration method in accordance with an embodiment of the invention is shown and indicated by the general reference character 200. The flow can begin in Start 202. Next, the substrate of a test wafer or a sample wafer can be etched for a given time (step 204). Next, the endpoint time of etch can be determined by independent means, e.g., "empirically" determined (step 206). One way to empirically determine the endpoint on the sample wafer is by performing a Scanning Electron Microscopy (SEM) analysis on the etched location of the sample wafer. Such a predetermining of the endpoint can allow for a "pinpointing" of the endpoint detection time on each harmonics plots. Accordingly, there can be a predetermined way of determining the endpoint (e.g., SEM analysis of a sample wafer) and then an observation of all available plots to empirically determine which one can provide the best correlated endpoint indicator.

[0027] Next, decision box 208 can route the flow back to step 204 if the endpoint time has not been detected. Otherwise, the flow can proceed to etch a new substrate beyond the endpoint time and record V-I probe signals (step 210). Next, the harmonics plots for a given RF frequency, including the parameters of voltage, current, and phase, can be analyzed and compared to determine the most sensitive signature of endpoint near the known endpoint time (step 212). Next, the endpoint harmonic algorithm can be defined (step 214). Of course, in some applications, the first harmonic or fundamental waveform may be the most appropriate for an endpoint detection according to embodiments. In one embodiment, the second harmonic for a voltage parameter at an about 2 MHz supply was found to provide the best endpoint detection for a dielectric etch application. Further, step 214 may include selecting a mathematical way (i.e., "algorithm") of finding the endpoint from the selected harmonics.

Such possible algorithms or methods will be discussed in more detail below. In one embodiment, the chosen algorithm and harmonic/parameter combination can be programmed in software located in Etch Process Module Controller 116 of FIG. 1, for example. Returning to FIG. 2, the flow can continue with etching a new substrate (step 216). Next, the endpoint accuracy can be verified with independent means (step 218). The flow can complete in step 220.

[0028] Referring now to FIG. 3, a flow diagram of a production environment endpoint detection method in accordance with an embodiment of the invention is shown and indicated by the general reference character 350. The flow can begin in Start 300. First, a wafer can be loaded (step 302). Next, etching can begin on the wafer (step 304). Next, the substrate (e.g., of a production wafer) can be etched while monitoring the V-I probe signal (step 306). Next, the V-I signals can be measured (step 308) and then analyzed (step 310). The analysis can include the use of conventional algorithms to detect an endpoint from a plot. Moreover, methods such as change in slope detection, amplitude comparison, or any standard technique that might be used for convention optical detection methods may be used, including multivariate techniques which combine multiple signals (e.g., voltage and phase). Also, a time window may be incorporated into the detection method whereby a time range where the endpoint is expected can be effectively highlighted on a harmonics plot. More details of endpoint detection from a plot will be discussed below with reference to FIG. 4.

[0029] In FIG. 3, after step 310, if the endpoint has not yet been detected, decision box 312 can route the flow to step 314 where the etching can be continued. The flow from step 314 can then proceed to step 308. If the endpoint has been detected, post-endpoint activities, such as etching for a designated additional time period or substituting another chemical or any other processing activity can be performed (step 316). The flow can complete in step 318.

[0030] There are many possible process recipes and wafer stack combinations that could be used according to embodiments of the invention. One example recipe used in testing methods according to embodiments of the invention is shown in the table below. FIGS. 4-6 show the associated harmonics waveforms and will be discussed in detail below.

Via (Oxide):	
BARC:	450mT / 0 W27 / 800 W2/O2/CH3F/200CO/N2/
Main Etch:	50mT / 2500W(27) / 3500W(2)/Ar/C4F8/O2/CH2F2 /CO/
Strip 1:	150mT / 200W(27) / 0W(2)/O2/CO/
Strip 2:	400mT / 0W(27) / 600W(2)/O2/CO/
Wafer-less auto-clean :	700mT / 500 W27 / 0 W2 /O2
SEM wafer stack info: Sematech patterned wafer: 61nm BARC / 10KA TEOS / 1KA TiN / Si.	

[0031] Referring now to FIG. 4, a graph of voltage harmonics waveforms for endpoint detection in accordance with embodiments of the invention is shown and indicated by the general reference character 400. This is an example waveform snapshot showing the possibility of using either a fundamental or a 2nd harmonic plot for endpoint detection. As discussed above, the general method may be to determine the best harmonic for a parameter (e.g., voltage, current, or phase) at a given RF frequency. Generally, the characteristics that may make one waveform preferable over another include the largest amplitude change about the endpoint as well as one that is repeatable and reproducible from wafer-to-wafer. Such repeatability is an important characteristic for production environments.

[0032] In FIG. 4, Waveform 402 shows a first harmonic (i.e., fundamental) plot of the voltage parameter for an RF frequency of about 27 MHz. From this graph, the endpoint can be determined corresponding to region 406. One such method of making this determination is an algorithm that looks for a trough and perhaps includes a filtering to smooth out the small manipulations (higher frequencies). Also, as mentioned above, a delay factor may be used to "bracket" or form a window around the endpoint because one may not expect an endpoint to

happen before or after a certain point in time. Other possible methods include using amplitude differences in signals, derivative functions, ratios, or any other standard techniques. Etch Process Module Controller 116 of FIG. 1 may, for example, perform the filtering and identifying of a trough for endpoint detection, as programmed by software control. In FIG. 4, Waveform 404 shows a 2^{nd} harmonic plot of the voltage parameter for an RF frequency of about 2 MHz. Similarly, the waveform shows characteristics for determining an endpoint, as shown. Accordingly, either of waveform 402 or waveform 404 may be effectively chosen and used for endpoint detection, according to embodiments of the invention.

[0033] Referring now to FIG. 5, a graph of phase harmonics waveforms for endpoint detection in accordance with embodiments of the invention is shown and indicated by the general reference character 500. Waveform 502 shows a first harmonic (i.e., fundamental) plot of the phase parameter for an RF frequency of about 27 MHz. From this graph, the endpoint can be determined, as indicated. Waveform 504 shows a 2^{nd} harmonic plot of the phase parameter for an RF frequency of about 2 MHz. As can be seen from the figure, the endpoint determination would be more difficult for the about 2 MHz phase parameter 2^{nd} harmonic than for the approximately 27 MHz phase parameter fundamental plot. Accordingly, another parameter and/or harmonic may be chosen to determine the endpoint for the approximately 2 MHz RF supply.

[0034] Referring now to FIG. 6, a graph of a current harmonic waveform for endpoint detection in accordance with embodiments of the invention is shown and indicated by the general reference character 600. Waveform 602 shows a 2^{nd} harmonic plot of the current parameter for an RF frequency of about 2 MHz. From this graph, the endpoint can be determined, as indicated. Accordingly, each of the parameters of voltage, phase, and current may have a harmonic suitable for endpoint detection according to embodiments of the invention. In other applications, other parameters and/or harmonics may provide the best endpoint detection plots.

[0035] For systems that provide RF power to both the top and bottom electrodes, a VI-probe can be provided with the bottom electrode alone, with the top electrode alone, or with each of the two electrodes. Fig. 7 shows an alternative implementation wherein a V-I probe 732 and associated DSP 734 are provided with the top powered electrode 704. V-I probe 712

and DSP 714 are provided with the bottom powered electrode 708. Top powered electrode 704 is also provided with associated components, including RF matching network 730, RF power supply 728, and top electrode insulator 738 for insulating top electrode 704 from grounded chamber 700. In the implementation of Fig. 7, the endpoint signal can be measured from V-I probe 712, V-I probe 732, or from both of the V-I probes.

[0036] While this invention has been described in terms of several preferred embodiments, there are alterations, permutations, and equivalents which fall within the scope of this invention. For example, there are three parameters: voltage, phase, and current in the exemplary embodiments, but any suitable number of parameters and/or combination of parameters may be employed. Furthermore, different harmonics may be preferable and may vary from one system or application to another and may be empirically determined for different systems or applications. Likewise, more phase system harmonics may be available as V-I probe systems improve and, accordingly, such available harmonics are within the scope of this invention. As a further example, a 5^{th}, 6^{th}, 7^{th}, etc. harmonic plot may provide the most effective endpoint detection according to an embodiment of the invention. As yet another example, although the RF frequencies of about 2 MHz, about 27 MHz, and about 60 MHz are mentioned as exemplary RF frequencies, any other RF frequency or suitable type of frequency applicable to a plasma processing system or the like may also be employed. It should also be noted that there are many alternative ways of implementing the system and methods of the present invention. It is therefore intended that the following appended claims be interpreted as including all such alterations, permutations, and equivalents as fall within the true spirit and scope of the present invention.